Draft version February 1, 2008
Preprint typeset using LaTeX style emulateapj v. 04/03/99

THE RELATION BETWEEN THE MID-INFRARED EMISSION AND BLACK HOLE MASS IN ACTIVE GALACTIC NUCLEI: A DIRECT WAY TO PROBE BLACK HOLE GROWTH?

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Draft version February 1, 2008

ABSTRACT

We use a large, heterogeneous sample of local active galactic nuclei (AGN) that includes Seyfert 1s, Seyfert 2s and PG quasars to investigate for the first time the relation between black hole mass ($M_{\rm BH}$) and mid-infrared nuclear emission. We find a clear relation between $M_{\rm BH}$ and $10\,\mu$m nuclear luminosity for these local AGNs. There are no significant differences between type 1 and type 2 objects, implying that the reprocessing of the $10\,\mu$m nuclear emission is not severely affected by geometric and optical depth effects. We also confirm that $M_{\rm BH}$ is related to the $2-10\,$keV X-ray luminosity, but only for the Compton thin galaxies. We present a theoretical basis for these empirical relations and discuss possible reasons for the observed scatter. Our results show that rest-frame $10\,\mu$m and hard X-ray luminosities (especially the former, which is applicable to all AGN types) can be powerful tools for conducting a census of BH masses at high redshift and for probing their cosmological evolution.

Subject headings: galaxies: active – galaxies: Seyfert – galaxies: nuclei – quasars: general – black hole physics

1. INTRODUCTION

The cosmological evolution of the black hole (BH) population is a fundamental property to constrain models of galaxy formation and evolution. In the last few years we have seen significant progress, especially for local galaxies where BH masses are now being measured. More importantly, the discovery of two fundamental correlations between the BH mass and the bulge luminosity (Kormendy & Richstone 1995; Magorrian et al. 1998) and the BH mass and the stellar velocity dispersion (Gebhardt et al. 2000; Ferrarese & Merritt 2000) suggests a tight link in the evolution of the BH and its galactic host.

To produce reliable statistics of BH masses at high redshift, one would need unrealistic amounts of observing time if the methods employed to determine BH masses in the Local Universe (see Section 2) were to be used. Thus, understanding the cosmological evolution of BHs requires finding a good indicator of the active galactic nuclei (AGN) luminosity, independent from the effects of obscuration and the viewing angle, and directly related to the BH mass.

Among the suggested AGN power indicators are the infrared luminosity, the narrow line region [O III]λ5007 line emission, the hard X-ray ($2-10\,$keV) emission, and the radio emission (e.g., Mulchaey et al. 1994). The $2-10\,$keV hard X-ray emission is only a good indicator of the intrinsic luminosity of the AGN for those cases where it is transmitted through the torus, that is, in Compton thin galaxies.

QSOs emit a significant fraction of their bolometric luminosity in the infrared (e.g., Sanders et al. 1989). The mid- and far-infrared emission in Sys and radio quiet quasars is predominantly thermal in origin, namely dust emission (e.g., Rieke 1978; Barvainis 1987; McAlary & Rieke 1988; Sanders et al. 1989; and recently Haas et al. 2000; Polletta et al. 2000). Moreover, Spinoglio, & Malkan (1989) found that the $12\,\mu$m flux is approximately a constant fraction of the bolometric flux in Seyfert (Sy) galaxies and quasars. These considerations suggest that the main parameter governing the mid-infrared behavior is the power of the central engine, almost independently of the geometry, dust content and dust properties of the central region.

For type 2 objects, the infrared emission at $\lambda \lesssim 5\,\mu$m may still be significantly affected by viewing angle effects (obscuration) and/or stellar contribution (Alonso-Herrero et al. 2001 and references therein). At $\lambda \gtrsim 20\,\mu$m there may be significant contributions from star formation and/or the underlying galaxy. These contributions are not easily disentangled from the AGN emission unless high spatial resolution imaging is used. Thus the nuclear $10\,\mu$m luminosity appears as a good choice to represent the AGN bolometric luminosity.

In this letter we explore for the first time the relation between the BH mass and the thermal $10\,\mu$m nuclear emission for a heterogeneous sample of low-redshift AGN: Sy 1s, Sy 2s, and PG quasars, and explore the possibility of using the mid-infrared luminosity of AGN as a representation of their BH mass. We also discuss implications for the BH growth and demographics over cosmological times.

2. THE DATA AND CORRELATIONS

We have compiled BH masses of local AGNs – Sy galaxies and PG quasars – derived using three methods and for which nuclear $10\,\mu$m fluxes are available (see Table 1 for the sample and references for the data). The most direct

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Table 1
AGNs and BH mass methods used for the $10\,\mu$m luminosity vs. BH mass relation.

Method	AGN	Ref
Reverberation Mapping	PG 0026+129*, PG 0052+251*, PG 0804+761*, PG 0844+349*, PG 1211+143*	1
	PG 1226+023*, PG 1229+204*, PG 1307+085*, PG 1351+640, PG 1411+442*	1
	PG 1426+015*, PG 1613+658*, PG 1617+175, PG 1700+51, PG 1704+608	1
	PG 2130+099*, Mkn 335*, Mkn 590*, Mkn 817, NGC 3227*, NGC 4051*	1
	NGC 4151*, NGC 5548*, NGC 7469*, 3C390.3*, Akn 120*, F 9*, IC 4329A*, Mkn 509*	1
	Mkn 279*, NGC 3516*, Mkn 841*, Mkn 766*, NGC 4593*	2
$M_{\rm BH} - \sigma_*$ relation	NGC 1386, NGC 1566, NGC 1667, NGC 2110*, NGC 3185, NGC 3362, NGC 3982	3, 4
	NGC 4388*, NGC 4579*, NGC 5252*, NGC 5273, NGC 5283, NGC 5347	3, 4
	NGC 5695, NGC 5929, NGC 5940, NGC 5953, NGC 6104 , NGC 7682	3, 4
	NGC 7674, Mkn 1, Mkn 3*, Mkn 348*, Mkn 530, Mkn 573, Mkn 744, Mkn 1040	3, 4
Stellar/Gas kinematics	NGC 1386, NGC 4258*, NGC 1068, Circinus, NGC 4945*	5
	NGC 4395* (upper limit)	6

Note.—The galaxies marked with * were used for the hard X-ray luminosity vs. BH mass relation (Figure 1, right panel).
References for $M_{\rm BH}$ and method: 1. Kaspi et al. (2000). 2. Compilation of Wandel (2002). 3. Nelson & Whittle (1995). 4. Ferrarese & Merritt (2000). 5. Compilation of Moran et al. (1999). 6. Filippenko & Ho (2001).
References for the $10\,\mu$m fluxes. PG quasars: Neugebauer et al. (1987) and Sanders et al. (1989). Sy galaxies: small aperture ground-based measurements from Rieke (1978); Maiolino et al. (1995); Krabbe, Böker, & Maiolino (2001); P. Lira (2001, private communication), and *ISO* fluxes from Clavel et al. (2000).

way is from spatially resolved stellar kinematics (see Ho 1999 for a review), and measurements of masers in disks around massive BHs (see Moran, Greenhill, & Herrnstein 1999 for a review).

In the case of bright active galaxies where the stellar emission is swamped by the AGN emission, the best technique to derive BH masses is reverberation mapping (see a review by Peterson 1993). For sample of AGNs analyzed in Kaspi et al. (2000) we have used the BH masses (and errors) derived from the mean of the FWHM velocity measurements.

The third and most indirect method uses the empirical relation between the BH mass and the stellar velocity dispersion (the $M_{\rm BH} - \sigma_*$ relation) found by Ferrarese & Merritt (2000): $\log M_{\rm BH} = 4.80(\pm 0.54)\,\log\sigma_* - 2.9(\pm 1.3)$. The $M_{\rm BH}$ errors here are dominated by the empirical correlation uncertainty rather than by the observational errors in σ_*. In Figure 1 we only plot the errors associated with the slope of the relation, that is, $\Delta\log M_{\rm BH} = 0.54\times\log\sigma_*$.

We also explore the $2-10\,$keV hard X-ray luminosity vs. BH mass relation for Compton thin AGNs based upon the good correlation found between the hard X-ray and the $10\,\mu$m luminosities in Sys and PG quasars (Alonso-Herrero et al. 2001, Krabbe et al. 2001). The $2-10\,$keV hard X-ray luminosities (corrected for absorption) are from Nandra & Pounds (1994), Lawson & Turner (1997), Bassani et al. (1999), George et al. (2000), Iwasawa et al. (2000), and the compilation in Alonso-Herrero et al. (1997). We have included a few low luminosity AGNs with available hard X-ray fluxes corrected for absorption (although mid-infrared fluxes were not available). These are NGC 3031, NGC 4594, NGC 6251 ($M_{\rm BH}$ from the compilation of Ho 2002), NGC 3079 ($M_{\rm BH}$ from Moran et al. 1999) and NGC 5194 ($M_{\rm BH}$ derived from the $M_{\rm BH} - \sigma_*$ relation, where σ_* is from Nelson & Whittle 1995).

When available we have used distances derived from surface brightness fluctuations (Tonry et al. 2001). For the rest of the galaxies distances were computed using $H_0 = 75\,{\rm km\,s^{-1}\,Mpc^{-1}}$.

3. DISCUSSION AND CONCLUSIONS

The relations between the BH mass and the $10\,\mu$m nuclear luminosity and $2-10\,$keV luminosity for our AGN sample are presented in Figure 1 (left and right panel respectively). The latter relation has been previously analyzed by Wandel & Mushotzky (1986) and Awaki et al. (2001) for a limited number of AGNs. Ho (2002) and Wu & Han (2001) have investigated the relationship between the radio nuclear and total power and the BH mass and found a good correlation for bright AGNs. Ho (2002) however finds that weakly active galaxies do not follow the same relation.

In a series of papers, McLeod & Rieke (1995), McLeod, Rieke, & Storrie-Lombardi (1999) and McLeod & McLeod (2001) have demonstrated that there is a relation between the nuclear B magnitude of quasars and the near-infrared luminosity of the host galaxy (that is, the stellar mass of the galaxy). This relation is also present in luminous infrared galaxies when the far-infrared luminosity is used to represent the bolometric luminosity (McLeod et al. 1999). McLeod & McLeod (2001) interpreted these relations as the maximum nuclear luminosity possible in a host galaxy of a given near-infrared luminosity (mass). In view of this relation and the good correlation between the BH mass and the bulge luminosity of the host galaxy it would not be unreasonable to expect a relation between the BH mass and the AGN luminosity represented by the $10\,\mu$m or the hard X-ray luminosities, the latter only for Compton thin objects.

In the hard X-ray vs. $M_{\rm BH}$ relation the lines ($\eta_{\rm Edd} = 0.01$ and $\eta_{\rm Edd} = 1$) are the Eddington ratios computed in Awaki et al. (2001, their figure 3) assuming a bolometric correction of $\frac{L_{\rm bol}}{L_{\rm X}} = 27.2$ (note that these authors

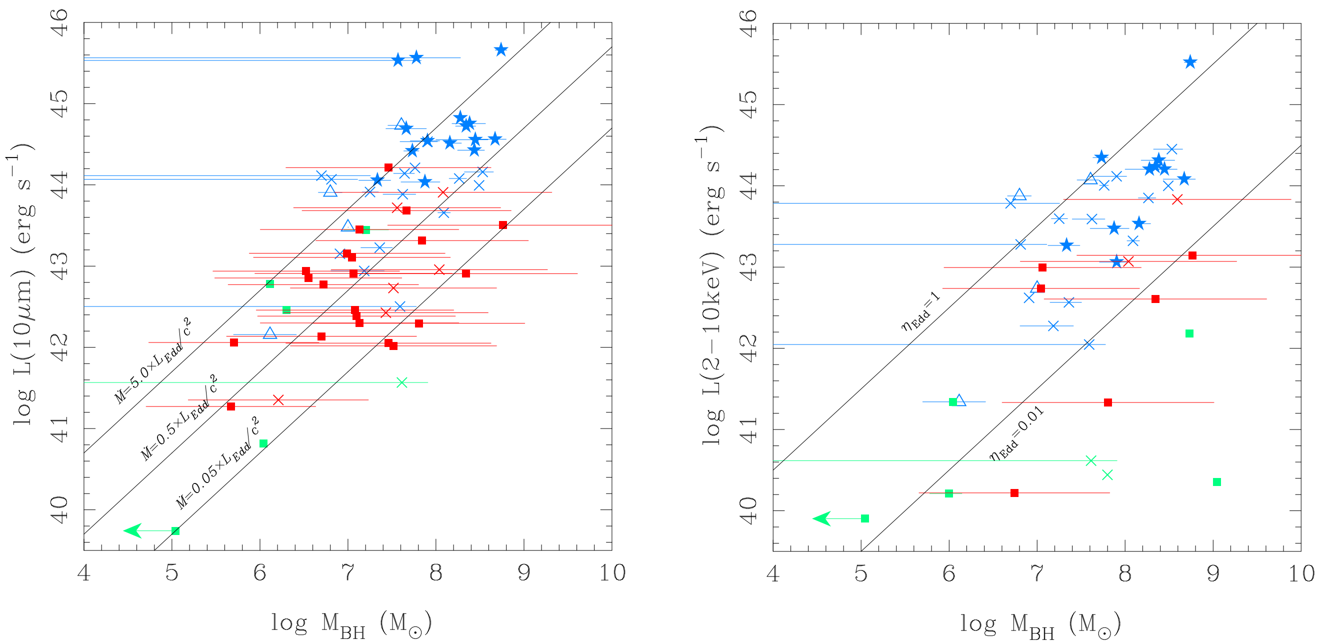

FIG. 1.— *Left panel:* Relation between the $10\,\mu$m nuclear luminosity and the BH mass. Filled stars are PG quasars, X's are Sy 1s, open triangles are NLS1s, and filled squares are Sy 2s. In the on-line version of this figure the data are color coded according to the method used for determining the BH mass: green from stellar/gas kinematics, blue from reverberation mapping and red from the $M_{\rm BH}-\sigma_*$ relation. *Right panel:* same as left panel but for the hard X-ray $(2-10\,{\rm keV})$ luminosity and BH mass.

pointed out that such bolometric correction may be lower for low luminosity AGNs). All the objects located to the right of the $\eta_{\rm Edd}=0.01$ line are low-luminosity AGNs. Although this is a good relation, it is only useful for Compton thin galaxies (column densities $N_{\rm H} \le 10^{24}\,{\rm cm}^{-2}$). Unfortunately for a significant fraction of type 2 objects the $2-10\,$keV X-ray emission is not transmitted through the torus (e.g., Bassani et al. 1999), and the $2-10\,$keV luminosities cannot be used to trace the obscured BH growth.

The scatter in the relations may be accounted for by efficiency variations in the accretion process in different kinds of AGN and/or evolutionary effects. The evolution will be relevant if the accretion rate is higher in the early growing stage of an AGN, as proposed by Mathur, Kuraszkiewicz, & Czerny (2001) to explain the properties of narrow line Sy 1 galaxies (NLS1s). This class of galaxies would represent an early stage of the AGN evolution based upon their lower BH to bulge mass ratios. The four NLS1s (shown as open triangles in Figure 1) in our sample show a similar behavior to the other Sy galaxies in both panels of Figure 1, if only with slightly higher accretion rates than the average. However the small number of NLSy1s does not allow us to reach a firm conclusion.

Another factor that may introduce some scatter in the mid-infrared vs. BH mass relation could be the presence of nuclear star formation in Sy 2 galaxies. If star formation were present (especially for those galaxies observed with the relatively large *ISO* aperture), we would expect an excess of $10\,\mu$m emission for a given BH mass. We do not find such excesses in our sample of galaxies. On the other hand, if the optical depths were high for type 2 objects even at $10\,\mu$m, then for a given BH mass they should lie below type 1 objects. Type 1 objects do not generally lie above type 2 objects in the $10\,\mu$m luminosity vs. BH mass diagram, suggesting that the reprocessing of the $10\,\mu$m nuclear emission is not severely affected by geometric and optical depth effects (see also Alonso-Herrero et al. 2001).

Hosokawa et al. (2001) and Kawaguchi, Shimura, & Mineshige (2001) constructed a disk-corona model to account for the X-ray through infrared spectral energy distributions (SEDs) of quasars and Sy galaxies. These models demonstrate that the AGN SEDs are sensitive to both the BH mass ($M_{\rm BH}$) and accretion rate ($\dot{M}$). In the optical, UV and soft X-ray spectral ranges decreasing $\dot{M}$ and/or increasing $M_{\rm BH}$ will move the peak of the SED toward longer wavelengths (i.e., figure 1 in Hosokawa et al. 2001). On the other hand, the hard X-ray and mid-infrared spectral shapes remain approximately constant for varying $M_{\rm BH}$ and $\dot{M}$. This is expected, as in this model the infrared bump is produced by dust heated by the AGN, and modelled with constant spectral indices, regardless of $M_{\rm BH}$ or $\dot{M}$. The infrared power varies so that the luminosity ratio of the big blue bump to the infrared bump remains constant.

The predicted $10\,\mu$m luminosity as a function of $M_{\rm BH}$ from Hosokawa et al. (2001) models is shown in Figure 1 (left panel) for two accretion rates[5] $\dot{M}=5-0.5\times L_{\rm Edd}/c^2$. The third accretion rate $\dot{M}=0.05\times L_{\rm Edd}/c^2$ curve has been extrapolated from the above mass accretion rates. The $10\,\mu$m luminosities of PG quasars are well reproduced with accretion rates of $\dot{M}=0.5-5\times L_{\rm Edd}/c^2$ (as found also by Kawaguchi et al. 2001 from the optical to X-ray properties), whereas Sy galaxies in general require lower

[5]For reference in this model a BH with an accretion rate of $\dot{M}=12\times L_{\rm Edd}/c^2$ will represent a disk with Eddington luminosity, $L_{\rm Edd}=1.5\times10^{38}\,\frac{M_{\rm BH}}{\rm M_\odot}$ (in erg s^{-1}) $L_{\rm Edd}$.

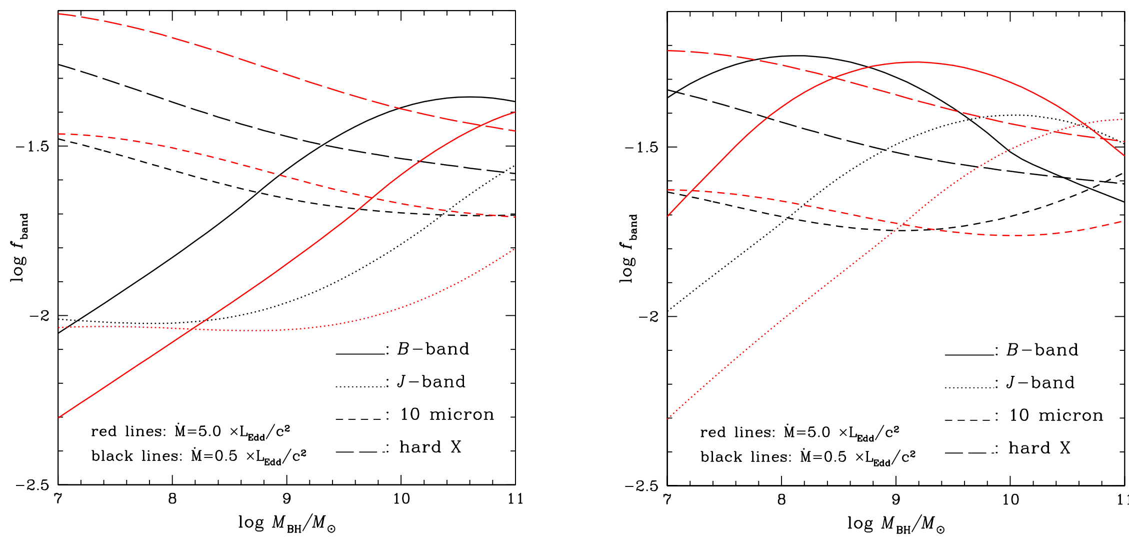

FIG. 2.— Predictions of Hosokawa et al. (2001) disk corona model for the ratio of the B-band, J-band ($1.2\,\mu$m), N-band ($10\,\mu$m) and hard X-ray ($2-10\,$keV) luminosities to the bolometric luminosity of the AGN as a function of $M_{\rm BH}$ at $z=0$ (left panel) and $z=3$ in the observer's rest-frame (right panel). The accretion rate is $\dot{M}=5\times L_{\rm Edd}/c^2$ (thin lines, red lines in the color version) and $\dot{M}=0.5\times L_{\rm Edd}/c^2$ (thick lines, black lines in the color version).

accretion rates (see also e.g., Su & Malkan 1989).

Figure 2 shows the ratio of the optical B-band, near-infrared J-band, $10\,\mu$m and hard X-ray to the AGN bolometric luminosity as a function of $M_{\rm BH}$ at two different redshifts $z=0$ (left panel) and $z=3$ (in the observer's rest-frame, right panel) from Hosokawa et al. (2001) model predictions. The accretion rate are $\dot{M}=5.0\times L_{\rm Edd}/c^2$ and $\dot{M}=0.5\times L_{\rm Edd}/c^2$. From this figure it is clear that the ratios of the $10\,\mu$m and hard X-ray luminosities to the AGN bolometric luminosity remain approximately constant for increasing $M_{\rm BH}$ at a given $\dot{M}$ over redshifts of $z=0-3$. Moreover, the ratio of the $10\,\mu$m luminosity to the AGN bolometric luminosity is also almost constant for the two accretion rates. This shows that the $10\,\mu$m luminosites can be used to trace the BH growth by comparing the mid-infrared luminosity functions at different epochs.

The optical to bolometric luminosity ratio varies significantly as a function of the BH mass for redshifts $z=0$ and $z=3$, and the two accretion rates. Although the J-band to bolometric luminosity ratio does only vary slightly with $M_{\rm BH}$ at $z=0$ and $\dot{M}=5.0\times L_{\rm Edd}/c^2$, it does significantly at $z=3$ for both accretion rates. Leaving aside the unavoidable obscuration (viewing angle) effects of type 2 AGNs, the complex dependence of the UV, optical and near-infrared SEDs with $M_{\rm BH}$ and $\dot{M}$ would make it more intricate the interpretation of the time evolution of luminosity functions to infer the BH growth.

There is now growing evidence for a missing population of obscured type 2 AGNs, necessary to reproduce the hard X-ray background (e.g., Fabian & Iwasawa 1999), as well as to reconcile the observed local comoving density of BHs with that predicted from the QSO luminosity function at $z=3$ (Haehnelt, Natarajan, & Rees 1998). This indicates that a significant fraction of the accretion by BHs may be obscured by dust. The two relations discussed here suggest that the hard X-ray luminosity and more importantly, the mid-infrared luminosity can be effective tools to probe the processes taking place in obscured nuclei of galaxies. These relations can be used to conduct a detailed census of the BH masses over a range of redshifts, and measure directly their growth rate as long as an estimate of the accretion rate is available. The present X-ray space missions are already producing results (e.g., Brandt et al. 2002 and references therein). The launch of *SIRTF* will provide further capabilities to obtain $M_{\rm BH}$ for obscured AGNs at redshifts of up to $z\simeq 4$.

Summarizing, for a heterogeneous sample of local AGNs we find: (i) the $M_{\rm BH}$ correlates with the $10\,\mu$m nuclear luminosity in local Sy galaxies and PG quasars; (ii) the available data suggest no significant differences between type 1 and type 2 objects, implying that the reprocessing of the $10\,\mu$m nuclear emission is not severely affected by geometric and optical depth effects; (iii) there is a good relation between the $M_{\rm BH}$ and the $2-10\,$keV hard X-ray luminosity, but only for Compton thin galaxies; (iv) the $M_{\rm BH}$ vs. $L(10\,\mu{\rm m})$ relation will allow to estimate the obscured BH mass growth over cosmological times using future observations with *SIRTF*.

We thank Dave Alexander, Roberto Maiolino and Laura Ferrarese for helpful discussions, and Paulina Lira for providing us with data prior to publication. We are also grateful to an anonymous referee for useful comments. AAH acknowledges support from NASA Contract 960785 through the Jet Propulsion Laboratory.

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